

Star formation in galaxies falling into clusters along supercluster-scale filaments

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ABSTRACT

With the help of a statistical parameter derived from optical spectra, we show that the current star formation rate of a galaxy, falling into a cluster along a supercluster filament, is likely to undergo a sudden enhancement before the galaxy reaches the virial radius of the cluster. From a sample of 52 supercluster-scale filaments of galaxies joining a pair of rich clusters of galaxies within the two-degree Field Redshift Survey region, we find a significant enhancement of star formation, within a narrow range between $\sim 2\text{--}3\ h_{70}^{-1}$ Mpc of the centre of the cluster into which the galaxy is falling. This burst of star formation is almost exclusively seen in the fainter dwarf galaxies ($M_B \geq -20$). The relative position of the peak does not depend on whether the galaxy is a member of a group or not, but non-group galaxies have on average a higher rate of star formation immediately before falling into a cluster. From the various trends, we conclude that the predominant process responsible for this rapid burst is the close interaction with other galaxies falling into the cluster along the same filament, if the interaction occurs before the gas reservoir of the galaxy gets stripped off due to the interaction with the intracluster medium.

Key words: Galaxies: clusters: general; Galaxies: evolution; large-scale structure of the Universe – cosmology: observations; Galaxies: starburst.

1 INTRODUCTION

In the past few years, several examples of spectacular starburst galaxies, often with significantly disturbed morphology, have been discovered on the outskirts of rich clusters of galaxies. Most of these have been found in deep images or spectral line studies of galaxies in rich clusters at redshifts of $z = 0.2\text{--}0.4$ (Moran et al. 2005; Sato & Martin 2006; Braglia, Pierini, Böhringer 2007; Marcillac et al. 2007; Einasto et al. 2007; Fadda et al. 2008). Some of these have been found in studies of nearby ($z < 0.1$) clusters as well (Sun & Murray 2002; Gavazzi et al. 2003; Haines et al. 2006; Reverte et al. 2007) though in the absence of systematic studies of large samples, it is not clear how common they are, and whether their presence is related to special properties of the clusters they are observed in, or to their large-scale environment, or indeed to the properties of the galaxies themselves.

The evolution of a galaxy is profoundly affected by its environment. Observationally, this has been established by studying the dependence of the relative morphological content of galaxies in a given volume of space, or of the colour or star formation properties of galaxies, on the local projected galaxy density. An obvious

place to look for such an effect is in galaxy clusters, which provide a wide range of galaxy densities as well as individual galaxy properties.

In the cores of rich clusters, the current star formation rate (SFR) in galaxies is found to be much lower than in the field, as measured from colour, morphology or spectral lines, progressively increasing as the environment becomes less dense (e.g. Melnick & Sargent 1977; Dressler 1980; Balogh et al. 2002; Lewis et al. 2002; Gómez et al. 2003; De Propriis et al. 2003; Kauffmann et al. 2004; Baldry et al. 2006; Poggianti et al. 2006; Pimbblet et al. 2006; Verdugo, Ziegler, & Gerken 2007). Whether the environment should be quantified by only the local projected density or not has also been the subject of scrutiny (e.g. Kauffmann et al. 2004; Blanton & Berlind 2007). Given that galaxies and groups are embedded in a network of clusters and filaments (Einasto et al. 1994; Jenkins et al. 2001), an interesting aspect of such studies is the investigation of how important the large-scale properties of the environment of a galaxy is in its morphological evolution, as well its history of star formation, merger and nuclear activity. Even though mergers and close interactions with other galaxies are most influenced by the local group environment of most galaxies (e.g. Hopkins et al. 2007), the potential effect of the larger-scale environment is undeniable, given that it would fundamentally affect the history of the parent group of the galaxy.

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Recently, Porter & Raychaudhury (2007) investigated the environmental dependence of star formation within three filaments (of length between 20–30 h_{70}^{-1} Mpc), joining rich clusters of the Pisces-Cetus supercluster. We observed that as one moves away from the cluster cores there is an increased activity of star formation, with a peak in the 3–4 h_{70}^{-1} Mpc range along the filaments over and above the gradual increase in star formation rate (SFR) away from the cluster cores. While this is a striking result, these results come only from approximately 1,000 galaxies in three filaments, and in one supercluster. To confirm that the observed effect is not confined to this one supercluster, a larger sample of filaments is therefore required. The Pisces-Cetus supercluster is the only “supercluster” found in the 2dFGRS survey from a study of all Abell clusters with a redshift of 0.1 from a minimal spanning tree analysis Raychaudhury et al. (in preparation) catalogue. To enlarge this sample of galaxies, we seek a larger survey of filament-like structures.

In this paper, we have compiled a subset of “clean filaments” (defined below) from the filament catalogue of Pimblet, Drinkwater, & Hawkrigg (2004) which listed 805 filaments identified from the galaxies of the 2dFGRS. We describe this sample in §2, and in investigate the star formation properties of galaxies belonging to these filaments as a function of distance from the nearest cluster. We discuss our results in §4 and our conclusions can be found in §5. Throughout this paper we use $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and a $\Omega_M = 1$ CDM cosmology. Using a concordance cosmology with a dark energy component affect only our distance measures, but not appreciably over the volume covered by our analysis.

2 THE SAMPLE OF FILAMENTS

Our parent filament catalogue (Pimblet, Drinkwater, & Hawkrigg 2004) is sourced from the 2 degree field galaxy redshift survey (2dFGRS; Colless et al., 2001) which in turn is based upon the APM survey (e.g., Maddox et al. 1990) as its photometric input catalogue. Here we summarise the most pertinent points, directing the interested reader to the filament catalogue paper for more detail.

2dFGRS galaxies are selected from the APM for observation to have an extinction corrected magnitude of $b_J < 19.45$ Using the final data release of 2dFGRS and combining cluster information (De Propris et al. 2002; Pimblet, Drinkwater, & Hawkrigg 2004) examined by the the region between >800 close cluster pairs (where clusters are within 10 degrees of each other and their difference in mean recession velocity is $<1000 \text{ km s}^{-1}$).

Further criteria were applied to narrow down the initial Pimblet, Drinkwater, & Hawkrigg (2004) sample of 805 potential filaments. Only filaments having a length of between 10 and 40 h_{70}^{-1} Mpc were selected. Further more, potential filaments that had a classification of “near coincidental clusters” or “Nil” were also removed. This resulted in a sample of 432 filaments to study visually. Each of the 432 filaments had two clusters from which Pimblet, Drinkwater, & Hawkrigg (2004) had identified a filament. In addition to these clusters other clusters fall within the same region of space. These extra clusters were deemed to be part of the filament if they had a redshift within 0.01 of the mean redshift of the two initial clusters and were coincident with the filament galaxies in R.A. and Dec. space. In addition, to confirm the presence of a cluster of galaxies at the cluster positions, each of the clusters had to have greater than ten members to be part of the filament. Cluster membership was determined by finding all 2PIGG (Eke et al.

Table 1. The 52 inter-cluster filaments for the 2dFGRS survey used in this study.

Clusters	Mean redshift	Filament length (h_{70}^{-1} Mpc)	EETMA Id
Abell 2829 Abell 0118	0.1133	20.75	9 ^a
Abell 2780 APMCC 0039	0.1031	33.62	9
EDCC 0465 Abell 2780	0.1046	40.13	9
Abell 2814 Abell 2829	0.1097	22.08	9
Abell 2829 EDCC 0511	0.1112	23.01	9
EDCC 0492 Abell 2804	0.1169	44.83	9
Abell 3094 Abell S0333	0.0675	13.07	49
Abell 1419 Abell 1364	0.1072	27.51	100,265
Abell 1411 Abell 1407	0.1334	21.41	
Abell 1692 Abell 1663	0.0834	17.41	126
Abell 1620 Abell 1663	0.0839	21.58	126
Abell 2553 EDCC 0275	0.1458	13.05	
Abell 3980 EDCC 0268	0.1894	27.04	
APMCC 0869 APMCC 0840	0.1125	47.62	
Abell 2601 Abell 4009	0.1091	42.68	299
EDCC 0365 Abell S1155	0.0547	38.71	
Abell 2741 APMCC 0039	0.1050	12.92	
Abell 2741 APMCC 0051	0.1060	21.07	
EDCC 0445 APMCC 0094	0.0617	17.94	
APMCC 0094 EDCC 0457	0.0613	20.86	
EDCC 0465 Abell 2814	0.1084	12.44	
Abell 2734 EDCC 0445	0.0623	17.94	10 ^b
EDCC 0457 EDCC 0445	0.0620	10.24	
EDCC 0517 EDCC 0511	0.1107	19.03	
Abell 2878 EDCC 0511	0.1090	24.14	
Abell 2915 EDCC 0581	0.0862	23.51	28
APMCC 0167 Abell S0160	0.0688	7.98	
Abell 2943 APMCC 0222	0.1498	21.36	
Abell 2961 APMCC 0245	0.1242	25.60	232
Abell 2967 Abell 2972	0.1122	12.03	232
Abell 2967 Abell 2981	0.1103	16.12	232
Abell 2981 Abell 2999	0.1083	15.84	232
EDCC 0119 Abell 3837	0.0885	28.84	190
EDCC 0057 Abell 3837	0.0922	25.07	190
EDCC 0057 APMCC 0721	0.0963	30.55	
Abell 3878 Abell 3892	0.1179	22.31	
EDCC 0230 APMCC 0827	0.1103	15.80	
APMCC 0827 Abell 3892	0.1142	31.64	
EDCC 0128 Abell 3880	0.0586	15.12	199
Abell 3959 APMCC 0853	0.0876	17.09	
Abell S1075 Abell 3978	0.0854	26.87	
EDCC 0457 Abell 2794	0.0613	20.86	
EDCC 0202 EDCC 0187	0.0768	8.85	
EDCC 0187 APMCC 0810	0.0769	7.24	
EDCC 0317 Abell 4011	0.1371	8.76	
EDCC 0321 Abell 4012	0.0533	9.49	
Abell 3854 Abell 3844	0.1505	29.89	
Abell S1064 EDCC 0153	0.0571	17.95	
EDCC 0239 APMCC 0853	0.0871	17.62	
EDCC 0248 Abell 3959	0.0876	17.09	
EDCC 0217 EDCC 0202	0.0784	19.94	
Abell 2493 EDCC 0215	0.0773	21.88	

^aSculptor Supercluster; ^bPisces-Cetus Supercluster (from Einasto et al. (2001)).

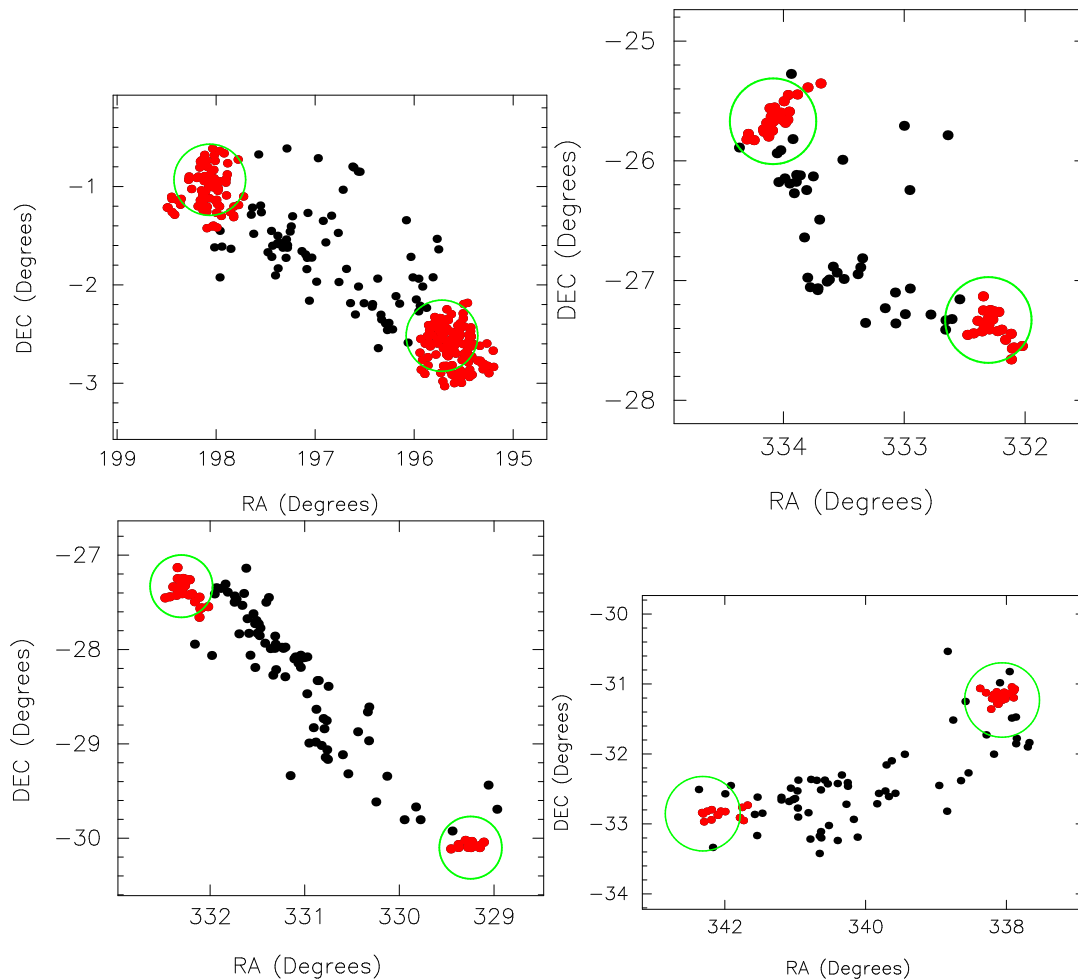


Figure 1. A few of the “clean filaments” used in this paper. The dots represent the galaxies from the 2dFGRS (with spectroscopic redshifts) included in these filaments joining the clusters (a) Abell 1692 and Abell 1663, (b) Abell 3837 and EDC 0119, (c) Abell 2660 and APMCC 917, and (d) EDC 365 and Abell S1155. Cluster members are shown in red, and the Abell radius ($2.1 h_{70}^{-1}$ Mpc) is shown as a green circle.

2004) group centres within $1 h_{70}^{-1}$ Mpc of the cluster centres. The members of these groups were then taken as the cluster members. Most clusters would correspond with a single 2PIGG “group” but for some, the 2PIGG catalogue had separated the cluster members into multiple “groups”.

From the sample of 432 filaments we created a “clean sample” of filaments. The filaments had to be between two clear clusters of galaxies and have to be relatively clean from contamination from other filaments and clusters. Therefore, by a visual inspection of the 432 filaments, 52 pairs of clusters on these filaments that had a clear run of galaxies, with no other intruding clusters within $6 h_{70}^{-1}$ Mpc, were found. To avoid contamination from the complex weave of other filaments, and to enable comparisons with our previous work, the galaxies joining the two filament clusters were selected using a method which extracts galaxies within a prolate spheroid.

We model each filament as a prolate spheroid, with the centres of the two clusters involved being at each end, the distance between them being the major axis of the spheroid, and $6 h_{70}^{-1}$ Mpc being the semi-minor axis. All galaxies inside this spheroid are assumed to be members of the filament, along the galaxies found to belong to the 2PIGG “group” corresponding to these Abell clusters in (Eke et al.

2004), to avoid leaving out the genuine cluster members that would not be included in the spheroid.

The distance between each pair of clusters, or that between a galaxy and a cluster, was calculated as the comoving proper distance between them. We used the measured redshift of each galaxy as a measure of its distance from us, except if it is a member of a rich cluster, where the mean redshift of the cluster was used.

This resulted in 6,222 galaxies within the 52 filaments. Examples of the spatial structure of these filaments can be seen in Figs.1, and a complete list of the filaments, and the clusters they connect, can be found in Table 1. Apart from Abell clusters, the cluster catalogue used to find filaments also use supplementary Abell (Abell S), Edinburgh-Durham (EDCC) and APM clusters (APMCC) within the same redshift range (Abell, Corwin, & Olowin 1989; Lumsden et al. 1992; Dalton et al. 1997). All references to 2dFGRS galaxies are taken from the 2PIGG subsample of the 2dFGRS (Eke et al. 2004) comprising 191,328 galaxies. This subsample had all the galaxies within fields with less than 70% completeness, and in all sectors (overlapping field areas) with completeness less than 50%, removed. This enables comparisons with 2PIGG statistics to be made without bias.

In the Table, we also list the corresponding supercluster in the Einasto et al. (2001, EETMA) catalogue, resulting from their analysis of the supercluster-void network from Abell rich clusters. Not all of our filaments correspond to their superclusters because of the different algorithm and cluster samples used in identifying filaments. It is interesting to note that the Sculptor supercluster, one of the most richest superclusters in the Einasto et al. (2001) study, features prominently in this Table.

3 STAR FORMATION IN GALAXIES ALONG THE FILAMENTS

The star formation properties of the 6,222 galaxies in the “clean sample” of filaments are investigated in this section. We look at their rate of star formation (represented by the η parameter) and the ratio of passive to star-forming galaxies, as a function of distance along the filaments.

To quantify the star formation properties of these galaxies, we use a simple parameter that has been derived for most 2dFGRS galaxies. Madgwick et al. (2002) used Principal Component Analysis (also see Folkes et al. 1999) of de-redshifted 2dF galaxy spectra to define a parameter η , a linear combination of the first two principal components, which correlates well with the equivalent width of the $H\alpha$ ($EW(H\alpha)$) emission line, which in turn is a measure of SFR (e.g., Kennicutt 1983; Gallagher, Hunter, & Tutukov 1984; Moustakas, Kennicutt, & Tremonti 2006). With some scatter, $\eta \approx -2.0$ correspond to no $H\alpha$ emission at all, increasing to $\eta \approx 7$ for $EW(H\alpha)$ of 50 Å (Madgwick et al. 2003). Thus, the η parameter can be used as a proxy for star formation rate in galaxies (see Porter & Raychaudhury 2005, 2007).

Fig. 2 shows the distribution of the η parameter for all 2dFGRS galaxies within $z \leq 0.1$, revealing two distinct peaks in the distribution, at $\eta \sim -2.5$ and at $\eta \sim 0.05$. This reflects the well-known bimodality of the local galaxy population, of red, passive galaxies, and bluer, star forming galaxies (e.g. Kauffmann et al. 2004; Balogh et al. 2004). The dip or divide between the two peaks is approximately at $\eta \sim -1.4$. The first peak, containing $\sim 30\%$ of the galaxies within $z < 0.1$, consists mostly of early-type galaxies (Madgwick et al. 2003). The SFR of a galaxy normalised to the Schechter luminosity L_* , is shown to be $\mu_* = 0.087 EW(H\alpha)$, where the $EW(H\alpha)$ is the stellar absorption corrected equivalent width of the $H\alpha$ line (Lewis et al. 2002). Therefore, an $\eta \sim -1.4$ would correspond to $\mu_* \sim 0.4$.

3.1 Star formation in galaxies as a function of distance from the nearest cluster

In this study of the star formation properties of galaxies, we look at the variation of (a) the mean value of the η parameter, which correlates with the current SFR of the galaxy, and (b) the fraction of galaxies with $\eta < -1.4$, representing the fraction of passive galaxies, as a function of position along the filaments and distance away from the nearest cluster.

For each of the 6,222 galaxies of the “clean sample” filaments, the distance of each from the nearest of the two clusters at either end of their parent filament is determined. The distances were then binned in varying size bins, aiming for approximately equal numbers of galaxies in each bin, and within each bin the mean η was calculated. The data for galaxies from all the filaments were combined and the means plotted against the mean distance in each bin and can be seen in see Fig. 3. For comparison between the trend

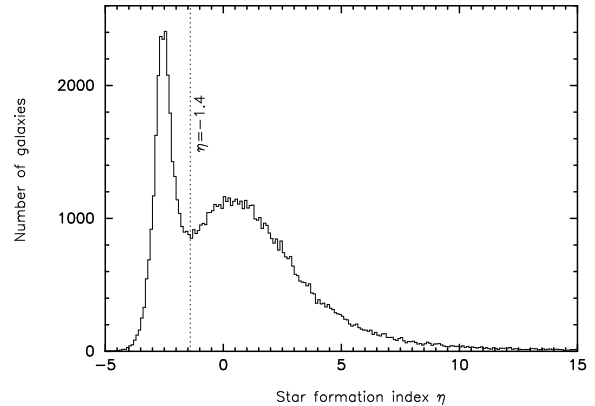


Figure 2. A histogram of the η parameter for all 2dFGRS galaxies within $z < 0.1$. The vertical dashed line is our adopted division between star-forming (larger η) and passive galaxies.

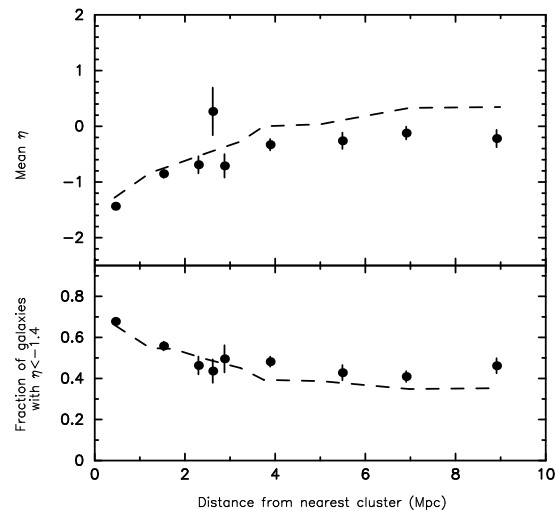


Figure 3. (a, Top) The mean value of η of galaxies belonging to the “clean” sample of 52 filaments, as a function of distance from the nearest cluster, is plotted here. The dashed line shows the mean η as function of distance from the nearest cluster (defined as a 2PIGG group with ≥ 30 members) for all 2dFGRS galaxies. (b, Bottom) For the same galaxies as in the top panel the fraction of these galaxies with an $\eta < -1.4$ is shown as a function of distance from the nearest cluster. The dashed line showing the same fraction as a function of distance from the nearest 2PIGG group with ≥ 30 members for the whole 2dFGRS.

with distance for the filament galaxies with galaxies elsewhere, we compute “field” values from the whole 2dFGRS, where distances are calculated from the nearest 2PIGG group of ≥ 30 members (the equivalent of a rich cluster), shown as the dashed line.

In order to statistically compare the two sets of points in Fig. 3, we use Welch’s t -test (Welch 1947), also known as the F -test (Press, Flannery, & Teukolsky 1986), which is an adaptation of the Student’s t test, for the comparison of two samples x_A and x_B with unequal variance $\sigma_A^2 \neq \sigma_B^2$. This statistic tests the null hypothesis that the means of the two samples are equal, assuming a normally distributed parent population, and returns a statistic

$$t = \frac{\langle x_A \rangle - \langle x_B \rangle}{\left[\frac{\sigma_A^2}{N_A} + \frac{\sigma_B^2}{N_B} \right]^{1/2}},$$

where N_A and N_B are the number of data points in the two samples. The test also a value for the significance of the difference of the two means, which is a number between 0 and 1.

In each of the 9 distance bins in Fig. 3, where the mean value of η is presented for two samples (the galaxies belonging to our filaments, and all galaxies in the 2dFGRS catalogue), we calculate the probability, that the means of the two samples are the same, in each distance bin. The results are shown in Table 2, where it is obvious that the two samples are similar in the first two bins, i.e. closer than $2 h_{70}^{-1}$ Mpc from the centre of each cluster. The galaxies on the inter-cluster filaments deviate appreciably from the general galaxy sample from the fourth bin onwards.

It can be seen that while the field galaxies show a gradual decrease in SFR as one moves from the periphery of the filament towards the cluster, steepening from approximately $2 h_{70}^{-1}$ Mpc inward, the filament galaxies show a sudden enhancement in SFR at about $2 h_{70}^{-1}$ Mpc on top of this gradual decline. This is very similar to the effect seen in the three filaments of the Pisces-Cetus supercluster, from a much smaller sample of galaxies (Porter & Raychaudhury 2007).

3.2 Star formation as a function of galaxy luminosity

It has been shown that the SFR in giant and dwarf galaxies show very different properties (e.g., Haines et al. 2006) and indeed, enhancements in SFR have been seen in dwarf galaxies at approximately the virial radius (e.g., Moran et al. 2005). In Porter & Raychaudhury (2007), we found that the peak in star formation along the Pisces-Cetus filaments is entirely due to the dwarf galaxies ($-20 < M_B \leq -17.5$).

Consequently, our sample of 6,222 galaxies was further segregated by environment into 1,392 giant galaxies ($M_B \leq -20$) and 4,830 dwarf galaxies ($-20 < M_B \leq -17.5$) respectively. As before we plot the mean value of η , and the fraction of passive galaxies, as a function of their distance from the nearest cluster, which can be seen in Fig. 4. However, the two separate samples are now plotted as open triangles for dwarf galaxies and filled circles for giant galaxies.

In each of the distance bins in Fig. 4, where the mean value of η is presented for two samples, the “dwarf” ($M_B > -20$) and giant ($M_B < -20$) galaxies, we calculate the probability that the means of the two sample are the same, according to the Welch test, in each distance bin. The results are shown in Table 2, where it is obvious the two sample are significantly different throughout the entire distance range.

It can be seen that the dwarf galaxies have a higher mean SFR than the giants at all values of distance from the nearest cluster. The striking revelation in this plot is that the abrupt enhancement in SFR, around a cluster-centric distance of about 2 Mpc, seen in Fig. 3, is almost entirely due to the dwarf galaxies.

3.3 Star formation in galaxies belonging to Groups

It has been suggested that much of the evolution of galaxies occurs in groups during their life on the filaments, before the groups are assimilated in clusters. This can be seen when the suppression of star formation with increasing local density of galaxies has been observed to occur at very low values of the local projected density ($\sim 1 h_{70}^{-1} \text{ Mpc}^{-2}$ (e.g. Lewis et al. 2002; Gómez et al. 2003). If this is the case the trend seen in the previous section would be different for filament galaxies that belong to groups and those that are

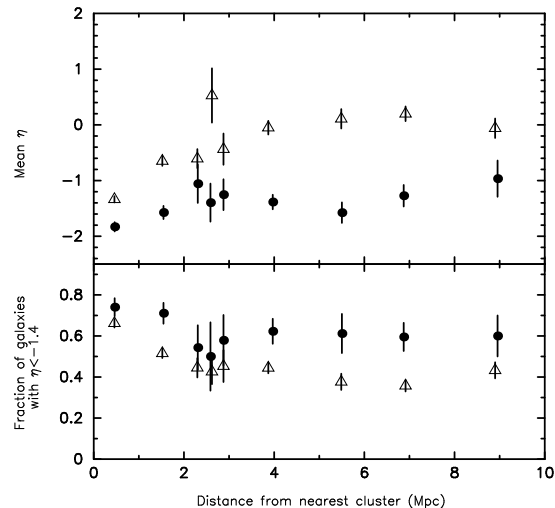


Figure 4. (a, Top) For the “clean filament” sample ($N=52$), the mean value η for giant galaxies ($M_B < -20$, closed circles) and dwarf galaxies ($M_B > -20$, open triangles), is plotted as a function of distance from the nearest cluster. (b, Bottom) The fraction of galaxies (same symbols) with $\eta < -1.4$, as a function of distance from nearest cluster.

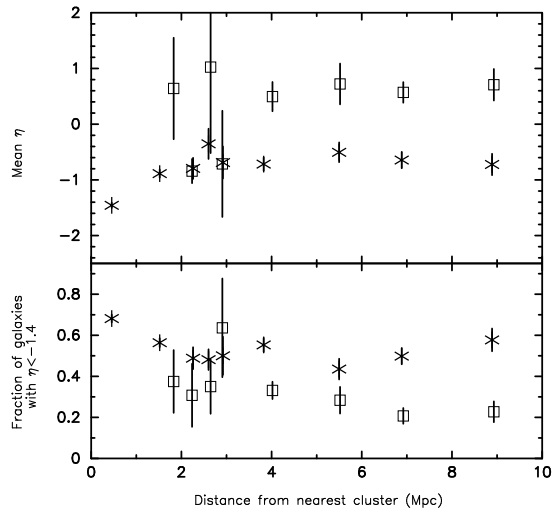


Figure 5. (a, Top) For the “clean filament” sample ($N=52$), the mean value of η as a function of distance from the nearest cluster. Galaxies that are members of groups (2PIGG groups with ≥ 4 members) and part of the filament are shown as crosses, while non-group galaxies are shown as squares. (b, Bottom) The fraction of galaxies (same symbols) with $\eta < -1.4$, as a function of distance from nearest cluster.

relatively isolated. We also note the significant evidence of galaxy-galaxy merger among the high and intermediate mass galaxies in poor groups, as evident from their luminosity functions (Miles et al. 2004; Miles, Raychaudhury, & Russell 2006).

We divided our galaxy sample into those that are a member of a group (defined to be a member of a 2PIGG group (Eke et al. 2004) that has 4 or more members), and those that are not (isolated galaxies or those that are members of 2PIGG groups of fewer than 4 members). The majority of the galaxies (4921) in our sample are part of groups (or clusters) according to this definition.

The mean value of η parameter, and the fraction of passive galaxies, as a function of their distance from the nearest cluster are

Table 2. Welch’s t -test results

Figure Number	1	2	3	4	5	6	7	8	9
Fig. 3	0.02	0.87	0.97	0.08	0.03	0.04	0.06	3.9E-3	6.5E-3
Fig. 4	1.1E-6	6.2E-10	0.24	0.001	0.04	3.9E-13	2.5E-10	1.5E-9	0.02

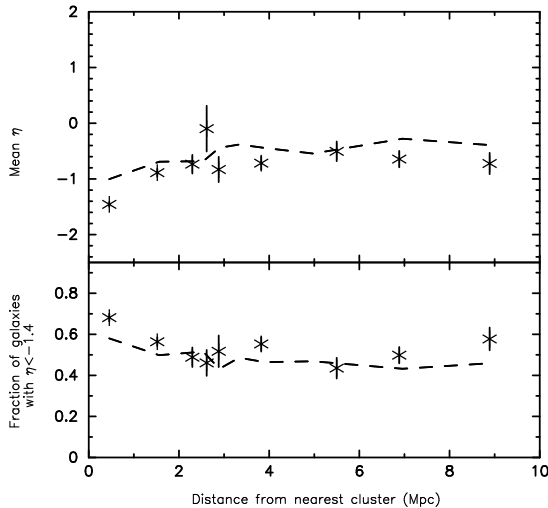


Figure 6. (a, Top) The mean value of the parameter η , as a function of distance from the nearest cluster, for galaxies belonging to 2PIGG groups (with ≥ 4 members) in the 2dFGRS. Of these, group galaxies that are also members of the 52 filaments described in this work, are shown as crosses, while galaxies that are part of groups elsewhere in the entire 2dFGRS shown as a dashed line. (b, Bottom) The fraction of galaxies (same symbols) with $\eta < -1.4$, as a function of distance from nearest cluster.

plotted in Fig. 5, which shows that the peak in mean η occurs in groups and non-group galaxies at approximately the same cluster-centric distance, but the non-group sample generally has a higher fraction of star-forming galaxies.

Fig. 6 compares these same quantities for galaxies that belong to groups that are part of filaments to similar group galaxies elsewhere in the 2dFGRS. The dashed line represents the variation of mean η , and passive galaxy fraction as a function of distance from the nearest cluster, of all galaxies belonging to groups (2PIGG, $N \geq 4$) in the 2dFGRS. The plot suggests that the star formation rate is more or less uniform in all group galaxies irrespective of their distance from the nearest cluster, except for those galaxies within the virial radii of clusters. The crosses with error bars represent the subset of these galaxies that belong to groups that are part of the 52 “clean sample” supercluster filaments studied in this work. There is some indication that the trend we find of a peak in SFR between $2-3 h_{70}^{-1}$ Mpc is seen in the group galaxies that belong to filaments, indicating that the presence of the filaments influences star formation properties in galaxies that belong to groups in this region.

4 DISCUSSION

At the outset, we mentioned the recent discovery of several instances of rapidly starbursting galaxies near the virial radius of rich clusters, with disturbed morphology suggesting strong interactions (e.g. Sun & Murray 2002; Moran et al. 2005; Reverte et al. 2007).

Does this occur at the periphery of every rich cluster, as galaxies are accreted from their surroundings as part of the hierarchical build-up of clusters? Does the incidence of such objects depend on the nature of the environments of clusters, and on the properties of the galaxies themselves? How common and important is this effect in the life of a typical galaxy, formed on the filamentary network of baryons as they are assimilated in the larger-scale scheme of the Universe?

Here we undertook a statistical study of this effect from a sample of clusters that can be seen to be fed by supercluster-scale filaments, from a substantial redshift survey in the nearby Universe. In order not to be confused by superposition effects, we selected a sample of “clean” inter-cluster filaments which do not have other structures superposed on them, and studied the star formation properties of galaxies as a function of position on these filaments and in clusters at their extremities.

We collectively stack galaxies in all of the chosen filaments, and look at the mean star formation rate, as well as the fraction of passive galaxies, as a function of the distance of each galaxy from its nearest rich cluster (see Fig.3). As expected, the SFR declines from the far outreach of the filament environment to the galaxies in the cluster core. This reveals the effect of a physical mechanism that quenches star formation progressively as a galaxy approaches the core of the cluster potential well (e.g., Balogh et al. 1998; Kauffmann et al. 2004; Pimbblet et al. 2006; Nolan, Raychaudhury, & Kabán 2007). However, as in our earlier study in the Pisces-Cetus supercluster (Porter & Raychaudhury 2007), we find the evidence for a sharp burst of star formation between $\sim 2-3 h_{70}^{-1}$ Mpc, which is about 1.5–2 times the typical virial radius, from the centre of the nearest rich cluster.

A typical disk galaxy formed in the relative sparse environment of a supercluster filament is expected to have reservoir of warm gas to provide for continued star formation in the galaxy. This gas can be in the range of temperatures $10^5 - 10^6$ K, which would account for X-ray emission, or it could be cooler and be undetected in the X-rays. Some evidence of such warm haloes has been found around nearby disk galaxies from Chandra observations (e.g., Pedersen et al. 2006).

In their analysis of redshift catalogues, Einasto (1991) found that the slope of the galaxy-galaxy correlation function is characteristic of near-spherical structures like groups and clusters for separations smaller than $3 h_{100}^{-1}$ Mpc, beyond which it becomes more representative of filamentary structures. It is interesting to note that the characteristic cluster-centric distance at which the peak of star formation is seen in this study is roughly half of this spatial scale. Such a transition is apparent from Fig. 1, where the Abell radius ($2.1 h_{70}^{-1}$ Mpc) is indicated, showing that on much larger scales, the predominant structures appear more filamentary than spherical. This may indicate that such scales ($2-3 h_{70}^{-1}$ Mpc) represent the zone of transition between the field from which galaxies are accreted into clusters, and the region in which the properties of the clusters become important in the evolution of galaxies.

As a galaxy comes closer than this to the centre of the individ-

ual cluster, into which it is falling, the dark matter halo of the cluster begins to exert important tidal and dynamical influence. A galaxy would possibly begin to encounter the hot intra-cluster Medium (ICM) of the rich cluster at this distance as well. As the gaseous halo of the galaxy interacts with the hot ICM, the galaxy may lose its reservoir of gas through evaporation and possibly ram pressure stripping. This will lead to a steep decline in the SFR of galaxies within $\sim 1 h_{70}^{-1}$ Mpc of the centre of the cluster, a trend that is seen in all relevant studies, including ours. Where this process of “strangulation” of star formation becomes important, galaxy-galaxy harassment (Moore et al. 1996) will also be an important effect. However, since most of the gas reservoir of the closely-interacting galaxies has been removed by this stage, star formation will not be induced by the harassment, and the remaining gas of the galaxy will continue to be stripped, leading to the observed steep dip in SFR in the first two bins in Fig. 3 from the centre of each cluster.

However, approaching the outer regions of the cluster along a filament, the infalling galaxies would experience close interactions among themselves, even before they experience any significant influence of the gravitational potential of the cluster, and that of its ICM, on their rate of star formation. Particularly for galaxies falling along crowded filaments into a cluster, the local density of galaxies would already have begun to increase rapidly, and it could be appreciable at distances as large as twice the virial radius. Therefore, the most likely cause for enhanced star formation that we observe in a narrow range of cluster-centric distances between $\sim 2\text{--}3 h_{70}^{-1}$ Mpc, would most likely be due to galaxy-galaxy harassment, which is a rapidly acting process, working efficiently in crowded environments. This effect would occur in addition to the general trend of decrease in SFR towards the core of the cluster, as found in galaxies elsewhere. These galaxies, still at relatively large distances from the cluster centre, yet to encounter the hot and dense ICM of the cluster, would have not had their gas stripped or evaporated, yet the close interaction with other galaxies flowing into the same cluster would lead to density fluctuations in their gaseous ISM, resulting in bursts of star formation.

In numerical simulations, galaxy-galaxy harassment is seen to be a rapid effect (e.g., Moore et al. 1999). This accounts for the narrow range over which the peak in the SFR is seen, since the effect depends on both the existence of substantial fuel for star formation (at a substantial distance from the cluster core), as well as sufficient external influence (due to strong interactions from nearby galaxies) which would act as trigger. Furthermore, the star forming galaxies will fall into the cluster with already elevated gas temperatures, which, when they encounter the ICM, will make them more prone to evaporation and stripping, which would steepen the gradient of the rapidly decreasing SFR. This effect may have been directly seen in the case of a starburst galaxy in a group (Rasmussen, Ponman, & Mulchaey 2006).

Within the virial radius of the cluster, the “backsplash” effect (Gill, Knebe, & Gibson 2005; Rines et al. 2005), resulting from a galaxy being on an oscillating orbit at the bottom of the potential well at the core of a cluster, is expected to be strongest at about ~ 1 Mpc from the centres of clusters, and thus is not likely to have a strong effect on the peak in SFR seen in our sharp peak in star formation, which occurs at larger cluster-centric distance.

Moran et al. (2005) observe a similar sharp peak in SFR (evident from redshifted [OII] emission) in the outskirts of the rich cluster CL0024 at $z = 0.4$, at $1.8 h_{70}^{-1}$ Mpc from the cluster centre, where galaxy harassment is cited as a possible cause. All of their starburst galaxies are dwarfs ($-20 < M_B$). At lower redshift,

a photometric study (Haines et al. 2006) of the nearby Shapley supercluster (Raychaudhury 1989; Raychaudhury et al. 1991) reveals an excess of blue star-forming dwarf galaxies ($M_R > -18$) at $\sim 1.5 h_{70}^{-1}$ Mpc from the centre of the rich clusters in the core of the supercluster. While it is encouraging to observe similar effects in other studies using different observables, the SFR peak found in the case of the Shapley supercluster or CL0024 is a factor of ~ 1.5 closer to the cluster core than the distance at which the SFR peak is found in our study. It is possible that the galaxies in 2dFGRS filaments experience the effect of galaxy-galaxy harassment at a larger distance from the cluster centre, since the accretion of galaxies in this case occurs along relatively narrow filaments, resulting in similar galaxy densities further out than would be seen in the case of clusters where galaxies are being accreted from all directions.

Fig. 4 shows that the galaxies of lower luminosity ($-20 < M_B \leq -17.5$) have a higher SFR than the giant galaxies at all distances from the cluster core. This is consistent with the results of other studies (e.g., Haines et al. 2006; Moran et al. 2005). This again provides more evidence for galaxy-galaxy harassment being the dominant process in producing the rapid burst in star formation, since dwarf galaxies are expected to be more vulnerable to galaxy harassment than giants. Furthermore, the small merger cross section of dwarf galaxies would make the merging of galaxies an unlikely cause of the dwarf dominated peak in SFR.

Finally, we investigated whether a galaxy belongs to a group (2PIGG group, $N \geq 4$) or not makes a difference to their star formation properties as they fall into clusters. Within the filaments, the SFR peak occurs in the same place for group galaxies as in non-group galaxies, though the peak is less pronounced in the former category. We find that in the filaments, the mean η of the non-group galaxies is higher than that of the group galaxies. The justification of this could be that galaxies in the groups will have been interacting with each other within the group environment long before they reach the infall regions of the clusters. They will therefore have had some of their gas already stripped off by galaxy-galaxy and galaxy-IGM interactions, by the time they reach their current position on the filament. Therefore, the group galaxies will not have as much of a fuel reservoir for continued star formation as the non group galaxies and so will have lower mean SFR.

At this stage, we admit to the caveat in the use of the η parameter as a proxy for current SFR, since the principal component analysis used in obtaining the η parameter will not have removed contributions from active galactic nuclei (AGN). It therefore remains a possibility that part of enhancement in mean η is due to AGN activity rather than conventional star formation, consistent with the results of Ruderman & Ebeling (2005), who find a prominent spike in the number of X-ray AGN in clusters at $\sim 2.5 h_{70}^{-1}$ Mpc. However, not all X-ray detected AGN have the usual emission lines in their optical spectra (Shen et al. 2007). Clearly, further studies should involve direct estimate of star formation rates from well-calibrated spectral line features.

5 CONCLUSIONS

From a study of galaxies belonging to three inter-cluster filaments in the Pisces-Cetus Supercluster, Porter & Raychaudhury (2007) had found that, in addition to the (expected) systematic decline in the star formation rate from the filament environment on the periphery of a cluster to the cluster core, there is a peak, representing a burst of star formation, over a narrow range of cluster-centric distance, at $\sim 2\text{--}3 h_{70}^{-1}$ Mpc (about 1.5–2 times the cluster virial

radius) from the centres of the clusters at the ends of each filament. However, these results were based on a few hundred galaxies in only three filaments, in one Supercluster.

In this work, we have repeated a similar analysis with a much larger sample of galaxies ($N=6,222$), in 52 different inter-cluster filaments, chosen from a redshift survey of a substantial fraction of the $z < 0.2$ Universe (from the 2dFGRS).

We chose a sample of “clean” filaments from a larger catalogue of supercluster filaments, requiring the filaments to connect two rich clusters of galaxies and be at least $6h_{70}^{-1}$ Mpc long with no intervening clusters within this distance. The filaments were chosen solely from their morphology without any knowledge of the star formation properties of the galaxies belonging to them.

For galaxies belonging to the “clean sample” filaments, we have also looked at similar dependence on distance of the fraction of passive galaxies, in each distance bin. In doing so, we have also noted whether these galaxies are giant ($M_B \leq -20$) or a dwarf, or are a member of a group or a cluster. Where possible, we have compared these results to similar properties of galaxies elsewhere in the 2dFGRS galaxy redshift survey.

We confirm that in the cores of rich clusters, the star formation rate in a galaxy is very low, irrespective of its mass, by showing that the value of mean η and the fraction of passive galaxies falls to its lowest value for both giant and dwarf galaxies in the cores of clusters. As one moves away from the cores of clusters along the filaments, there is an increased activity of star formation, peaking at approximately $2-3 h_{70}^{-1}$ Mpc, at approximately 1.5 times the virial radius of the clusters. This peak in star formation in filament galaxies is seen to be mostly due to dwarf galaxies ($-20 < M_B \leq -17.5$).

The sudden enhancement in the star formation rate witnessed in our sample (see Fig.3) is a rapidly acting process such as galaxies experiencing the intracluster medium for the first time or galaxy harassment. As galaxies just start to encounter the ICM they will not yet have had their gas stripped or evaporated, but the interaction with the ICM will lead to tidal shocks leading to a burst of star formation. Similarly, with their gas still intact, galaxy harassment may lead to density fluctuations in the gas which may trigger a burst of star formation. In the infall region of the cluster at a few h_{70}^{-1} Mpc, the galaxies will just have started to accelerate to the velocities needed for galaxy harassment to become an important factor. The sharpness of the peak in SFR is another indicator that galaxy harassment may be important, since Moore et al. (1999) show that harassment is a rapid effect.

Within the filaments, the abrupt enhancement in star formation occurs in the same place outside the virial radius of the cluster, for galaxies belonging to 2PIGG groups, as in non-group galaxies, though the peak is less pronounced in galaxies belonging to groups. We suggest that this due to the close interaction of galaxies within groups causing some of the gas content of the galaxies to be stripped away, before they experience the galaxy-galaxy harassment that is responsible for the enhancement, even before they fall into the cluster.

Using the η parameter, which is derived from optical spectra, and known to correlate with the current rate of star formation of a galaxy, we have been able to show that on filaments feeding clusters, the current star formation rate of a galaxy, particularly that of a dwarf, is likely to undergo a sudden burst due to the close interaction with other galaxies falling into the cluster along the same filament, if the interaction occurs before the gas reservoir of the galaxy gets stripped off due to other effects. The direct detection of these galaxies, often excluded from narrow-field studies of the cores of

clusters, should be possible from the detection of dust from *Spitzer* observations. From deep X-ray observations, it would also be interesting to study how the group environment around each galaxy (characterised by the hot IGM) affects its star formation rate, as the group is assembled into the rich cluster.

Finally, we would also like to point out that others have found similar starburst and IR-luminous galaxies in the inner parts of certain rich clusters as well (e.g. Keel et al. 2003; Duc et al. 2004; Cortese et al. 2007). The use of directly measured star formation parameters, instead of proxies like the η parameter will also reveal (e.g. Mahajan & Raychaudhury 2008) interesting aspects of galaxy properties in such environments. As larger samples of such cases emerge, it would be interesting to investigate whether these galaxies are actually near the virial radius of the cluster, but seen in projection to be closer to the centre, or if there are other physical effects, applying to a category of galaxies, that protect the fuel for star formation from being stripped as the galaxy falls into the core of a cluster. Numerical simulations with appropriate resolution and detailed hydrodynamical modeling of the gas-galaxy interaction (e.g. Berrier et al. 2008), would be necessary to further investigate the relative importance of various physical processes affecting galaxy evolution over this range of distances.

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